D/3

Preceding page blank

HELICOPTER RESEARCH PROBLEMS

By Alfred Gessow

Langley Aeronautical Laboratory

INTRODUCTION

This paper is restricted to a presentation of the more important problems associated with the development of the most successful type of rotating-wing aircraft - the helicopter - and to an indication of the present status of research of these problems.

The helicopter as thought of at present is an aircraft in which lift, propulsion, and control are all provided by one or more propeller-like rotors turning about an approximately vertical axis. The fundamental advantage of such an arrangement is that the means for obtaining and controlling flight is separated from the translational speeds of the fuselage. In spite of the many advantages afforded by this feature, notably that of vertical flight, it was only during the last decade that helicopters having satisfactory performance and handling qualities have been built and flown. Their success can be attributed to improved power plants, an increased knowledge of general aerodynamics as well as the aerodynamics of rotating-wing flight, and the backlog of experience gathered from the hundreds of unsuccessful helicopter builders since the time of Da Vinci.

The present-day helicopter is still in an early stage of development. Its performance, handling characteristics, safety, and reliability, however, though still poor when judged by modern airplane standards, are already acceptable for a number of important applications where its special capabilities are at a premium. Prospects for further improvement are good and a wide field of application, both military and commercial, is assured.

DISCUSSION

The general helicopter research field is, for the present discussion, divided into four broad classifications: performance, vibration and flutter, stresses, and stability and control. A description of the problems encountered in each of these fields is given, and lines of future research are pointed out.

Performance

The problem of determining the aerodynamic characteristics of a lifting rotor for purposes of design or performance estimation is complicated by the large number of variables involved. Consequently, the approach could not be wholly empirical, and some theoretical frame work was required to correlate experimental data. The performance problem has been attacked therefore by trying to develop a method of calculating the characteristics of the rotor from the characteristics of the blade airfoil sections. The method is similar to that of calculating propeller characteristics by blade element or strip theory but is much more complicated because of the flapping motion of the hinged blades and because the translational (edgewise) component of velocity in forward flight must also be accounted for.

In order to make the problem capable of practical solution, certain assumptions and simplifications had to be incorporated in the theory in addition to the primary one of using two-dimensional airfoil characteristics in summing up the forces acting on the blades of the rotor. A principal assumption specified that the rotor induced velocity could be calculated by the momentum theory and could be considered to be uniform across the rotor disk. (See reference 1.) The resulting calculations, which were extremely lengthy and complicated, were simplified and condensed into design charts that give a good insight as to the effects of changes in rotor design parameters. (See reference 2.) Sufficient comparisons of the theory with experimental data have been obtained from flight and full-scale tunnel tests to prove the validity of theory. (See references 3 to 9 for an experimental verification of the theory in various flight conditions.)

The accuracy of the theory is illustrated by figure 1, which shows the good agreement between the calculated and measured characteristics, as obtained in flight, of a test rotor in terms of a plot of power against velocity. It might be mentioned that model tests in general are not satisfactory for helicopter-performance work because of the effects of scale on the aerodynamic characteristics of the blade elements.

The transition region between hovering and about 30 miles per hour shown in the figure represents a speed range in which accurate data could not be obtained in flight because of instability and control difficulties or in full-scale wind tunnels because of the largely unknown interference corrections at low airspeeds. Full-scale data were obtained in this region, however, by means of a relatively new research tool - the helicopter test tower. It was found that the test-tower results checked closely with theoretical calculations over most of the transition region.

As a result of the experience gained through the use of the theory and its experimental verification, several factors were found to influence considerably the performance characteristics of rotors. One such factor was the importance of smooth, nondeformable blade surfaces in reducing the power required by the rotor in all flight conditions. (See references 9 and 10.) The importance of well-built blades arises from the fact that in cruising and high-speed flight blade profile drag accounts for from one-half to two-thirds of the total rotor losses.

Rotor theory and experiment have also shown that rotor performance is dependent to an appreciable extent on the amount of twist and taper built into the blades of the rotor. Studies (reference 11) have indicated, for example, that the rotor induced losses, which are the penalty that must be paid for the thrust produced by the rotor, comprise approximately 75 percent of the total power losses in the hovering condition and that these losses can be reduced to the extent of increasing the hovering pay load by approximately 20 percent if the blades were designed with a moderate amount of taper and twist, instead of being untapered and untwisted.

Theory and experiment have also pointed out the values of design variables that would result in maximum performance. An example of this is illustrated in figure 2, which shows the importance of low rotor speeds and high blade lift coefficients for hovering and vertical-flight performance. The top curve shows that a reduction of tip speed from 600 feet per second to 400 feet per second would reduce the power required to hover at fixed thrust by approximately 25 percent. The lower curve shows that at a fixed power and thrust, the same reduction in tip speed results in a substantial increase in the vertical rate of climb, namely from 200 feet per minute to approximately 1150 feet per minute. The question might naturally arise as to what constitutes a lower limit to the tip speed and why the helicopter couldn't always operate at that limiting condition. The answer lies in the fact that low tip speeds are very undesirable at high speeds and that a good helicopter design must either compromise between the two conditions or must deliberately favor one at the expense of the other. (See reference 12.)

The choice of the proper tip speed and other design parameters for efficient high-speed flight must be investigated as part of the general problem of rotor-blade stalling. This problem has received and is getting a great deal of attention, inasmuch as it considerably reduces the efficiency of a helicopter flying at high speeds and is the decisive factor in limiting the top speed of present-day helicopters.

Blade stalling results from the fact that as the lifting rotor moves forward, the advancing blades encounter progressively higher velocities, whereas the retreating blades encounter progressively lower velocities. Thus, in order to maintain approximately equal lift on both sides of the rotor so as to prevent the helicopter from rolling over, the low-velocity retreating blade must operate at higher angles of attack than the high-velocity advancing blade. It follows that as the helicopter increases its forward speed, the angles of attack of the retreating blade will increase proportionally until at some value of forward speed the angles of attack of the retreating blade will reach the stall. As still higher speeds are reached, the stalling becomes progressively more severe and spreads to a larger part of the rotor disk until the severe vibrations and the loss of control brought about by the stall prevents the helicopter from flying faster.

The effect of forward speed and rotor tip speed on stalling is illustrated in figure 3. The circles represent plan views of the rotor disk, the direction of flight and direction of rotation being as shown.

The dark region at the center represents the swept area of the hub and blade shanks and the shaded crescents represent the regions where the direction of flow over the retreating blades is reversed. For this helicopter, at 40 miles per hour and 210 rotor rpm, stall is beginning to occur near the tip of the retreating blade. When the speed is increased to 70 miles per hour, still keeping the same rotor rpm, the stalled area has increased considerably. The reduction in stalled area brought about by increasing the rotor speed to 225 rpm is shown on the bottom circle. At the same forward speed, the higher rotational speed reduces the differential in speed between the advancing and retreating blades and so cuts down the stalled area.

A criterion has been developed for predicting the limiting speed due to stalling. (See reference 13.) It has been found that the operational limit can be considered as reached when the calculated angle of attack at the tip of the retreating blade exceeded the stalling angle of the blade airfoil by approximately 4°. One use of this criterion is illustrated in figure 4 which shows the variation of the minimum allowable rotor speed, as set by blade stalling, with forward speed. The minimum rotor speed was calculated for each value of forward speed by setting a 16° tip angle of attack at the retreating blade as the operational limit. Thus, for a given forward speed, a helicopter cannot be operated in the hatched portion of the plot but must increase its rotor tip speed until the tip angle of attack is 16° or less (that is, it must be operated to the right of the curve.)

Although a helicopter can be flown until the 4° tip-angle limit is exceeded, the profile-drag loss due to stalling begins as tip stalling sets in. It has been found that the profile drag approximately doubles by the time the limiting top speed is reached. (See reference 14.) The effects of stalling on rotor profile drag can be seen in figure 5, in which the profile-drag power absorbed by two sets of blades are plotted against speed. The dashed lines in the figure represent the calculated power with no allowance for blade stalling, whereas the solid lines include losses due to stalling and thus represent the actual profile-drag power absorbed. Note that stalling losses are large in comparison to the profile-drag power absorbed by the unstalled blades and that, therefore, the top speed of the helicopter is also reduced because of the additional stall power.

Once the effects of blade stalling were understood, means for alleviating or delaying these effects were investigated. A satisfactory way to delay the stall was to twist the rotor blades so that the tip sections worked at lower angles of attack than they would if the blades were untwisted. (The effects of blade twist were investigated in flight and the results are reported in reference 15.) The effectiveness of blade twist in reducing the detrimental effects of stalling can be seen in figure 5. The figure shows that an increase of about 10 percent in the limiting speed of the test helicopter appears possible with the use of -8° of blade twist. Alternatively, twist reduces the stalling profile-drag losses by approximately 40 percent of the profile-drag power absorbed by the rotors in the unstalled condition once stalling had developed on both rotors. The use of blade twist is desirable inasmuch as, at the very least, it appears to have no detrimental effect on rotor performance in any other flight condition.

Another and somewhat obvious means for minimizing the effects of blade stalling is by increasing the blade-section stalling angle of attack. The benefits to be had by so doing, in terms of an increase in permissable load at a fixed tip speed, is shown in the left part of figure 6. It can be seen from the figure that the permissable helicopter load could be increased by a factor of 3 if the section stall angle could be increased from 12° to 20°. The successful application of various high-lift devices that would substantially increase the section stall angle without prohibitive drag increases in the high-velocity low-angle-of-attack regions of the disk will prove a fertile field for future helicopter research.

Just as blade stalling presents a lower limit to the allowable rotor tip speed, another limit exists that prevents operation at extremely high tip speeds. That limit is compressibility effects on the high-velocity tip sections of the advancing blade. For a given stalling angle, a higher section critical Mach number will permit operation at larger gross weights because it permits the use of higher tip speeds. It can be seen from the right part of figure 6 that large increases in pay load can be realized by increasing the critical Mach number of airfoil sections used in the blades.

Although most rotor blades at the present time are composed of conventional wing sections, attention is being given to the development of airfoil sections designed especially for rotors as distinguished from wings or propellers. In addition to a high stall angle and a high critical Mach number, the desirable aerodynamic characteristics of airfoil sections suitable for use as rotor-blade sections are: (1) nearly zero pitching moment, (2) low drag throughout the range of low and moderate lifts, and (3) moderate drag at high lifts.

Most of the NACA low-drag airfoils that have been developed have too high a pitching-moment coefficient to warrant consideration for use with current helicopter designs. (High pitching-moment coefficients lead to undesirable periodic stick forces and to vibrations brought about by periodic blade twist.) Although this objection is removed with the low-drag symmetrical sections, these sections are not applicable because half of the low-drag "bucket," or, in other words, half of the limited range of lift coefficients in which the important drag reductions are achieved, is below zero lift; whereas the faster moving portions of the helicopter blade are nearly always operating at positive lift coefficients.

In order to place the low-drag "bucket" in a useful range of lift coefficients and still retain zero or almost zero moment coefficient, a number of special airfoils have been derived. (See reference 16.) One of these, the NACA 8-H-12, shows the most promise. A comparison of the

NACA 8-H-12 section with the conventional NACA 23012 airfoil is given in figure 7, which shows a reduction in drag over most of the lift coefficient range combined with an earlier stall. Calculations of the performance of rotors incorporating the new section have indicated the superiority of the special section over the conventional sections. Full-scale tests of practical-construction blades incorporating the NACA 8-H-12 section are needed, however, to determine the true worth of the airfoil under actual operating conditions.

Vibration and Flutter

It is commonly accepted that where large, rotating masses are involved, vibrations of some kind are likely to appear - and the helicopter is no exception. In fact, the designers of most of the earlier types of helicopters had as much difficulty in reducing the vibration to acceptable levels as they had in obtaining adequate performance. A good deal of the trouble was caused by poorly built, unbalanced blades and was largely eliminated with more accurate designs and an increased knowledge of blade balancing and tracking procedure. A second source of the vibration difficulties encountered were inherent in the helicopter itself and could only be avoided when the phenomenon that caused it was thoroughly analyzed and understood. An example of such a phenomenon is a self-excited mechanical vibration known as "ground resonance," which has been responsible for the destruction of several autogiros and helicopters.

Essentially, "ground resonance" is a self-excited mechanical vibration that involves a coupling between the motion of the rotor blades about their drag hinges and the motion of the helicopter as a whole on its landing gear. When the frequencies of the two motions approach each other, a violent shaking of the aircraft occurs which, if undamped, would result in its complete destruction. This phenomenon was theoretically investigated and a theory was developed which suggested means for avoiding "ground resonance." (See references 17 to 19.) In order to make the theory easy to use, it was put in the form of simple charts which predicted the range of rotor speeds in which the instability occurred and the amount of damping necessary to avoid dangerous frequencies.

Another example of a vibration problem peculiar to helicopters was encountered in the operation of two-bladed rotors. The phenomenon was called blade "weaving" from the appearance of the wavy path traced by the blade tips and was found to be an aerodynamic instability or type of flutter. The problem was investigated theoretically (reference 20) and also by means of model tests. The general result of the study was that a see-saw rotor with a coning angle is more unstable than an airplane wing having corresponding parameters. The additional unstabilizing effect is associated with the difference in moments of inertia in flapping and in rotation. In fact, it was found that with certain combinations of coning angles and blade design parameters, flutter could occur even when the chordwise center of mass of the blades was well ahead of the 25-percent-chord point. Proposed remedies for the flutter investigated included decreasing the coning angle of the blades, designing the blades so that their mass tends to be confined to the plane of rotation, increasing the control-system stiffness and forward position of the center of mass, and adding mechanical damping to the rotor system.

The helicopter is subjected to a third type of vibration that cannot be eliminated inasmuch as it is a forced vibration inherent in the aerodynamics of the rotor itself. This type of vibration is encountered, for example, with two-bladed helicopters in the transition region between hovering and forward flight wherein cyclic variations of induced and profile drag give rise to horizontal hub vibrations or, for example, when blade stalling is encountered in high-speed flight. (See reference 21.) Although inherent vibrations of these types cannot be eliminated, they can be isolated by suitably shock mounting the rotor system, and by using irreversible controls that cannot transmit vibratory forces to the pilot's controls. A great deal of work remains to be accomplished in reducing the over-all vibration level of the helicopter so that it can be flown for long periods of time without unnecessarily adding to pilot fatigue.

Stresses

Although the achievement of maximum helicopter performance and reliability calls for a thorough knowledge of the stresses imposed on the rotor and fuselage of the helicopter in all steady and accelerated flight conditions, the general field of helicopter stress analysis has been considered secondary to the aerodynamic problems. Literature on helicopter stress analysis does exist, but, in the main, conventional methods have been applied in analyzing the fuselage and rotor blades. Blade analyses, for example, have been made by propeller strip methods although an additional complication that has been taken into account is the spanwise bending of the blades, which tends to change the direction of the centrifugal loading on the blades. (See references 22 to 26 for information on blade stress analysis.) As yet, however, actual stress values, and the various assumptions regarding blade loading that are incorporated in these methods, have not been directly verified by reliable full-scale test measurements. Aside from a direct check on the actual stresses, the significance of these calculations would be greatly strengthened if experimental data were obtained on the induced flow in forward flight, so that the aerodynamic loading can be more accurately calculated. (The induced flow in hovering has been directly verified by British flight tests.)

In connection with induced-flow measurements, it might be mentioned that the over-all magnitude and general distribution of the induced velocity have been verified by rotor-blade-motion and performance tests made in flight. The induced velocity actually appears to vary nonlinearly in magnitude across the disk, however, and would therefore be expected to influence considerably local stress values along the blade. The problem of determining induced velocities is amenable to theoretical solution; and although some work has been done along these lines (reference 27), a good deal still remains to be done before rotor-blade stresses can be predicted with confidence.

Stability and Control

The information that has been accumulated on the stability and control of helicopters during the past years has been rather limited. In their desire to establish the practicability of the helicopter as a flying machine, designers have concentrated on improving the performance and reducing the vibrations of the helicopter, while accepting marginal stability and control characteristics. As a result, the helicopter in its present stage of development is different and more difficult to fly than most fixed-wing airplanes. In response to the increasing demands placed upon the helicopter by the armed services and by commercial operators, however, the improvement of the stability and control characteristics of the helicopter and of its flying and handling qualities is perhaps the most important helicopter research problem at the present time.

A number of theoretical papers have been written on the subject of helicopter stability and control. (See references 28 to 32.) Although the theories presented in these papers are somewhat different and sometimes contradictory, it is generally agreed that (1) if the helicopter is disturbed while hovering, and if the control stick remains fixed, the helicopter will describe an oscillation about its original hovering position, and (2) the amplitude of the oscillation will increase with time. According to definition, the helicopter is thus dynamically unstable in hovering. Calculations indicate that the period of the oscillation of a two-place, 2700-pound helicopter is of the order of 10 seconds and that the rate of divergence is small. Limited flight data, obtained in this country (reference 33) and in England, have roughly checked the calculations and have indicated that the instability of the hovering oscillation is not a problem to the pilot.

The helicopter does have some handling characteristics in hovering that are frequently objectionable, especially to the novice pilot. One of the handling problems that the trainee must overcome with the smaller sized helicopter arises from the high control sensitivity of the helicopter in roll or, in other words, the high rate of roll per inch of stick displacement. This sensitivity frequently leads to over-controlling, which may result in a short-period pilot-induced lateral oscillation. Control sensitivity becomes less of a problem with large machines because for a given stick displacement the rolling velocity obtained will vary inversely as the diameter. Frequently, undesirable stick-force gradients are additional factors that add to the control problems of the unexperienced helicopter pilot.

Another control difficulty that might be mentioned has been encountered in the partial-power vertical-descent region between approximately 500 and 1500 feet per minute. In this vertical-descent range, the vibration of the helicopter becomes quite pronounced. Rather violent, random yawing motions then occur with some roll; the rate of descent apparently increases rapidly; the rotor rotational speed varies noticeably; and more often than not the helicopter eventually pitches nose down and recovers by gaining speed, despite application of considerable rearward control. There is much to be learned about this regime of operation, but preliminary indications are that the fundamental cause of the phenomenon is an unsteady, mixed flow of air through the rotor. Irregular flow in this intermediate flight condition might logically be expected inasmuch as air is blown downward through the rotor in hovering, whereas in completely power-off descent an upward flow of air takes place. Although pilots have experienced no difficulty in recovering from the maneuver at any stage desired, the phenomenon could be dangerous if it occurred at very low altitudes.

The helicopter has certain undesirable stability and control characteristics in forward flight as well as in hovering and in vertical descents. The major complaint reported by pilots is that they find it quite difficult to hold steady conditions in forward flight because of a strong tendency of the machine to diverge in pitch. Investigation has shown that this tendency results from the fact that the helicopter in general is unstable with angle of attack. There are two logical sources for this instability. The first source is the usual unstable fuselage, and the second results from the flapping of the rotor. When a flapping rotor is subjected to an angle-of-attack change in forward flight, the resulting change in blade flapping will be such as to further increase the rotor angle change.

Theoretical calculations indicate that the instability of the rotor and fuselage with angle of attack, if not overcome by a stabilizing means such as a tail surface, results in an unstable dynamic oscillation. Flight test results of stick-fixed oscillations, reported in reference 34, qualitatively checked the calculations. An example of an oscillation obtained at 40 miles per hour is shown in figure 8. The oscillation was initiated by a momentary aft motion of the stick. The period of the motion is about 14 seconds, which is long enough so that the pilot does not have trouble controlling the oscillation. The motion doubles in amplitude in about 1 cycle. Results obtained at higher speeds, however, have indicated that the motion following a disturbance is a divergence, rather than an oscillation. As you can well imagine, a divergent motion that could be brought about by a sudden gust is a dangerous maneuver if corrective action is not immediately initiated.

An example of such a maneuver obtained at 65 miles per hour is shown in figure 9. Again the helicopter was disturbed by an intentional stick motion, after which the stick was held fixed at the trim position. The helicopter nosed up mildly and then nosed down. It was still nosing down at an increasing rate, as the acceleration curve indicates, about 4 seconds after the 1 g axis was crossed, and recovery had to be made by control application. In fact, considerable difficulty was encountered in recovering from the maneuver because the acceleration continued to build up 2 seconds after the cyclic control stick was at its forward stop. The pilot had to reduce the total pitch and had to roll the machine as in a wing-over before steady flight could be reached.

In general, it was found that though the helicopter is unstable over the entire speed range, its instability is least in the 40 to 60 miles per hour region. At higher speeds, the pilot has progressively less time to initiate recovery from a disturbance and the machine becomes rapidly more unstable.

It should be understood that the undesirable stability and control characteristics just discussed do not prohibit the present-day helicopter from being a useful tool for specialized purposes. Various means for eliminating these characteristics are under consideration in order to utilize all the potentialities of the helicopter, but the choice and application of these solutions depend upon continued research and development.

Future Research Needs

An attempt has been made herein to acquaint the reader with the present status of helicopter research. It may therefore be appropriate to conclude with a statement on future research needs.

Requirements for satisfactory flying qualities of helicopters should be established, similar to those already set up for the airplane, and means for meeting these requirements should be investigated. In particular, methods should be found to give the helicopter stick-fixed and stick-free stability in hovering and in forward flight. With this in mind, automatic-flight devices should be investigated; and the effectiveness and application of aerodynamic servocontrols and other control arrangements, including power controls, should be studied. Also, theoretical and experimental studies are needed to explain and correct the control difficulties encountered by pilots in the transition region between hovering and cruising flight and when descending vertically at partial-power conditions.

The trend toward large-diameter load-carrying helicopters calls for a more extensive knowledge of rotor-blade aerodynamic loading and blade stresses. Induced velocity and stress measurements should, therefore, be made and thoroughly analyzed. The use of more than one lifting rotor on the large load-carrying helicopters calls for a thorough investigation of the aerodynamic characteristics of the various multirotor arrangements that are being proposed. In particular, induced flow studies should be made for the various configurations that are now being used. Such studies would be useful for stability work and, also, for performance inasmuch as induced power requirements appear to be the primary unknown in computing the performance characteristics of multirotor configurations.

The application of jet propulsion to helicopters has long been considered as a desirable means for increasing the simplicity and the load-carrying ability of the helicopter. Several helicopters utilizing the jet principle have already been built and flown. A great deal of research, however, is still needed to establish the aerodynamic requirements of jet-driven helicopters and to produce an efficient jet system. The use of jets also brings about additional problems involving blade design, vibration, and stability characteristics that should be anticipated and solved.

It is hoped that an early and successful solution of these problems will make the helicopter a truly dependable and indispensable aircraft.

REFERENCES

1. Bailey, F. J., Jr.: A Simplified Theoretical Method of Determining the Characteristics of a Lifting Rotor in Forward Flight. NACA Rep. No. 716, 1941.

2. Bailey, F. J., Jr., and Gustafson, F. B.: Charts for Estimation of the Characteristics of a Helicopter Rotor in Forward Flight. I - Profile Drag-Lift Ratio for Untwisted Rectangular Blades. NACA ACR No. L4H07, 1944.

3. Gustafson, F. B.: Flight Tests of the Sikorsky HNS-1 (Army YR-4B) Helicopter. I - Experimental Data on Level-Flight Performance with Original Rotor Blades. NACA MR No. L5C10, 1945.

4. Gustafson, F. B., and Gessow, Alfred: Flight Tests of the Sikorsky HNS-1 (Army YR-4B) Helicopter. II - Hovering and Vertical-Flight Performance with the Original and an Alternate Set of Main-Rotor Blades, Including a Comparison with Hovering Performance Theory. NACA MR No. L5D09a, 1945.

5. Gessow, Alfred, and Myers, Garry C., Jr.: Flight Tests of a Helicopter in Autorotation, Including a Comparison with Theory. NACA TN No. 1267, 1947.

6. Dingeldein, Richard C., and Schaefer, Raymond F.: Full-Scale Investigation of the Aerodynamic Characteristics of a Typical Single-Rotor Helicopter in Forward Flight. NACA TN No. 1289, 1947.

7. Myers, Garry C., Jr.: Flight Measurements of Helicopter Blade Motion with a Comparison between Theoretical and Experimental Results. NACA TN No. 1266, 1947.

8. Migotsky, Eugene: Full-Scale Investigation of the Blade Motion of the PV-2 Helicopter Rotor. NACA TN No. 1521, 1948.

9. Gustafson, F. B., and Gessow, Alfred: Analysis of Flight-Performance Measurements on a Twisted, Plywood-Covered Helicopter Rotor in Various Flight Conditions. NACA TN No. 1595, 1948.

10. Gustafson, F. B.: Effect on Helicopter Performance of Modifications in Profile-Drag Characteristics of Rotor-Blade Airfoil Sections. NACA ACR No. L4H05, 1944.

11. Gessow, Alfred: Effect of Rotor-Blade Twist and Plan-Form Taper on Helicopter Hovering Performance. NACA TN No. 1542, 1948.

12. Gustafson, F. B., and Gessow, Alfred: Effect of Rotor-Tip Speed on Helicopter Hovering Performance and Maximum Forward Speed. NACA ARR No. L6A16, 1946.

13. Gustafson, F. B., and Myers, G. C., Jr.: Stalling of Helicopter Blades. NACA TN No. 1083, 1946.

14. Gustafson, F. B., and Gessow, Alfred: Effect of Blade Stalling on the Efficiency of a Helicopter Rotor as Measured in Flight. NACA TN No. 1250, 1947.

15. Gessow, Alfred: Flight Investigation of Effects of Rotor-Blade Twist on Helicopter Performance in the High-Speed and Vertical-Autorotative-Descent Conditions. NACA TN No. 1666, 1948.

16. Stivers, Louis S., Jr., and Rice, Fred J., Jr.: Aerodynamic Characteristics of Four NACA Airfoil Sections Designed for Helicopter Rotor Blades. NACA RB No. L5K02, 1946.

17. Coleman, Robert P.: Theory of Self-Excited Mechanical Oscillations of Hinged Rotor Blades. NACA ARR No. 3G29, 1943.

18. Feingold, Arnold M.: Theory of Mechanical Oscillations of Rotors with Two Hinged Blades. NACA ARR No. 3I13, 1943.

19. Coleman, Robert P., and Feingold, Arnold M.: Theory of Ground Vibrations of a Two-Blade Helicopter Rotor on Anisotropic Flexible Supports. NACA TN No. 1184, 1947.

20. Coleman, Robert P., and Stempin, Carl W.: A Preliminary Theoretical Study of Aerodynamic Instability of a Two-Blade Helicopter Rotor. NACA RM No. L6H23, 1946.

21. Seibel, Charles: Periodic Aerodynamic Forces on Rotors in Forward Flight. Jour. Aero. Sci., vol. 11, no. 4, Oct. 1944, pp. 339-342.

22. Owen, J. B. B.: The Stressing of Gyroplane Blades in Steady Flight. R. & M. No. 1875, British A.R.C., 1939.

23. Duberg, John E., and Luecker, Arthur R.: Comparisons of Methods of Computing Bending Moments in Helicopter Rotor Blades in the Plane of Flapping. NACA ARR No. L5E23, 1945.

24. Flax, Alexander H.: The Bending of Rotor Blades. Jour. Aero. Sci., vol. 14, no. 1, Jan. 1947, pp. 42-50.

25. Yuan, Shao Wen: Bending of Rotor Blade in the Plane of Rotation. Jour. Aero. Sci., vol. 14, no. 5, May 1947, pp. 285-293.

26. Horvay, Gabriel: Stress Analysis of Rotor Blades. Jour. Aero. Sci., vol. 14, no. 6, June 1947, pp. 315-336.

27. Coleman, Robert P., Feingold, Arnold M., and Stempin, Carl W.: Evaluation of the Induced-Velocity Field of an Idealized Helicopter Rotor. NACA ARR No. L5E10, 1945.

28. Sissingh: Contributions to the Dynamic Stability of Rotary-Wing Aircraft with Articulated Blades. Part I - General Principles. Translation No. F-TS-690-RE, Air Materiel Command, July 29, 1946.

29. Sissingh: The Dynamic Stability of Helicopters with Articulated Rotors - Second Partial Report. Translation No. F-TS-1002-RE, Air Materiel Command, Sept. 9, 1946.

30. Hohenemser, K.: Stability in Hovering of the Helicopter with Central Rotor Location. Translation No. F-TS-687-RE, Air Materiel Command, Aug. 1, 1946.

31. Hohenemser, K.: Longitudinal Stability of the Helicopter in Forward Flight. Translation No. F-TS-688-RE, Air Materiel Command, Aug. 2, 1946.

32. Donovan, A. F., and Goland, M.: The Response of Helicopters with Articulated Rotors to Cyclic Blade Pitch Control. Jour. Aero. Sci., vol. 11, no. 4, Oct. 1944, pp. 387-398.

33. Gustafson, F. B., and Reeder, J. P.: Helicopter Stability. NACA RM No. L7K04, 1948.

34. Reeder, John P., and Gustafson, F. B.: Notes on the Flying Qualities of Helicopters. Paper presented at the Fourth Annual Forum of the American Helicopter Society (Philadelphia, Penna.), April 22-24, 1948.

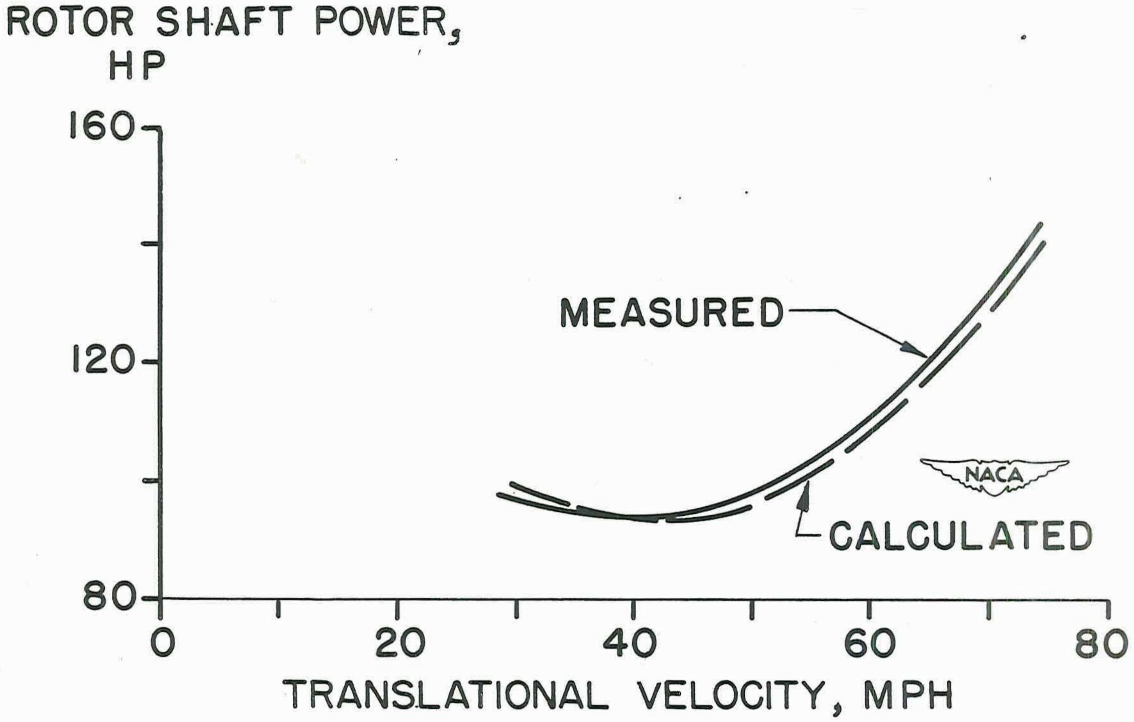

Figure 1.- Comparison of rotor characteristics as calculated and measured in flight.

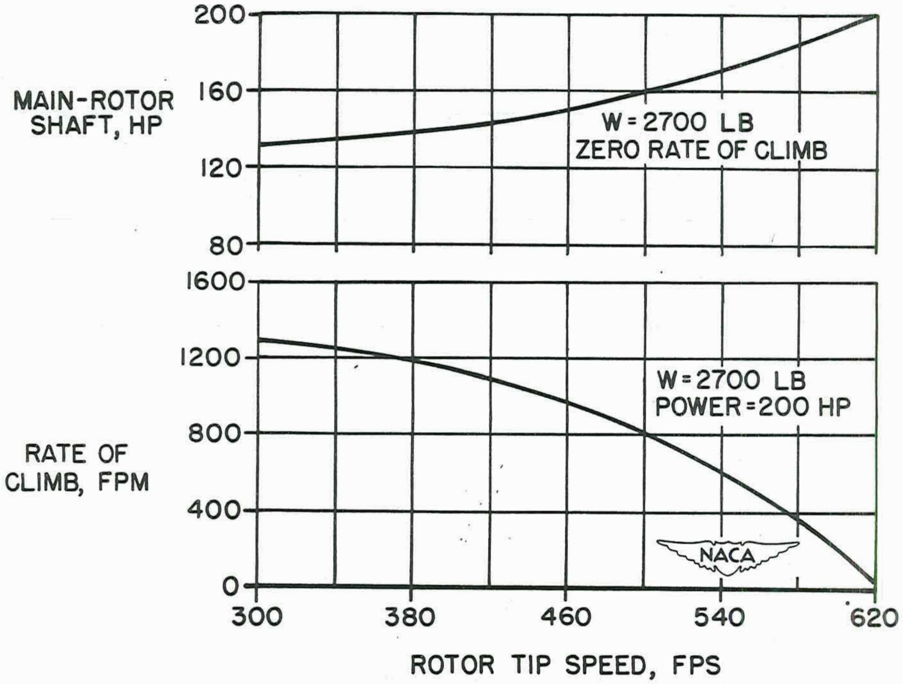

Figure 2.- Effect of rotor tip speed on hovering and vertical flight performance of sample helicopter.

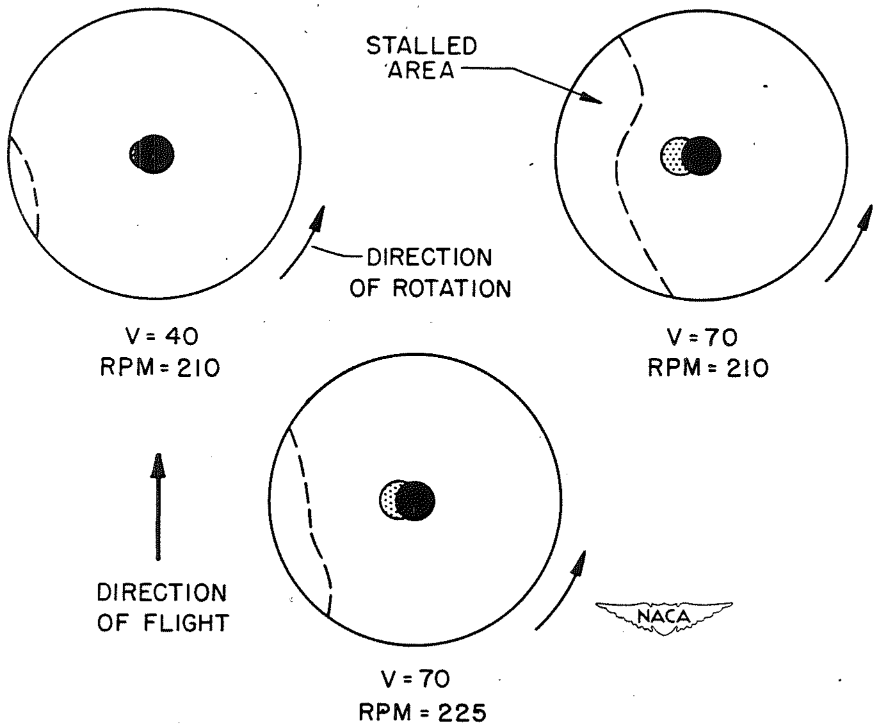

Figure 3.- Effect of forward speed and rotor tip speed on rotor-blade stall.

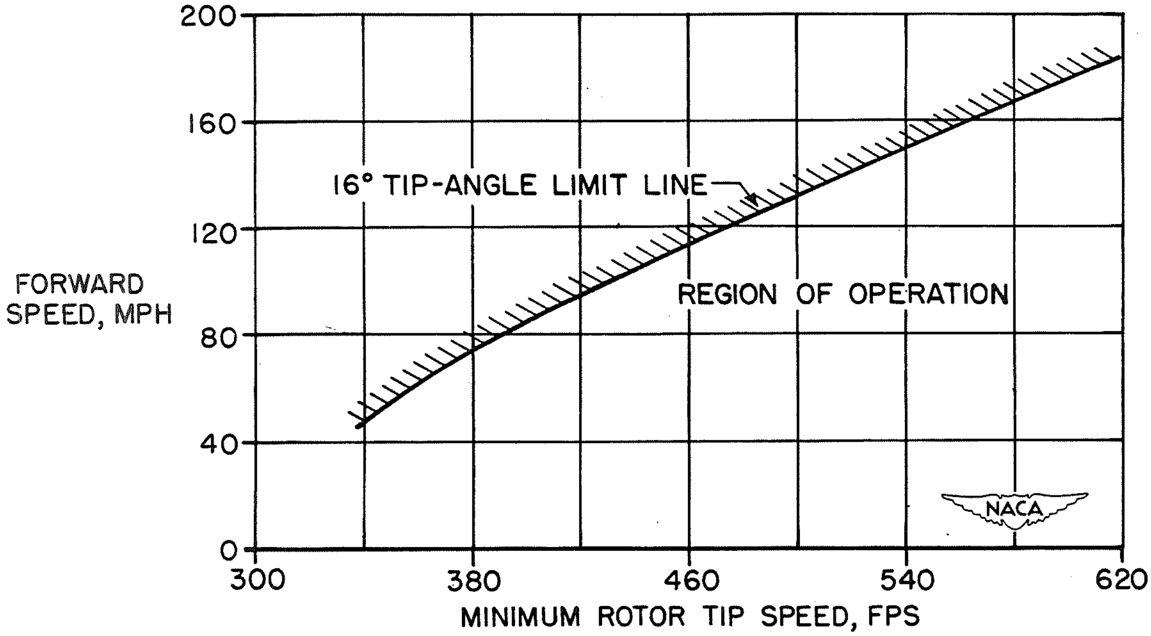

Figure 4.- Variation of minimum rotor tip speed, as set by rotor-blade stall, with forward speed.

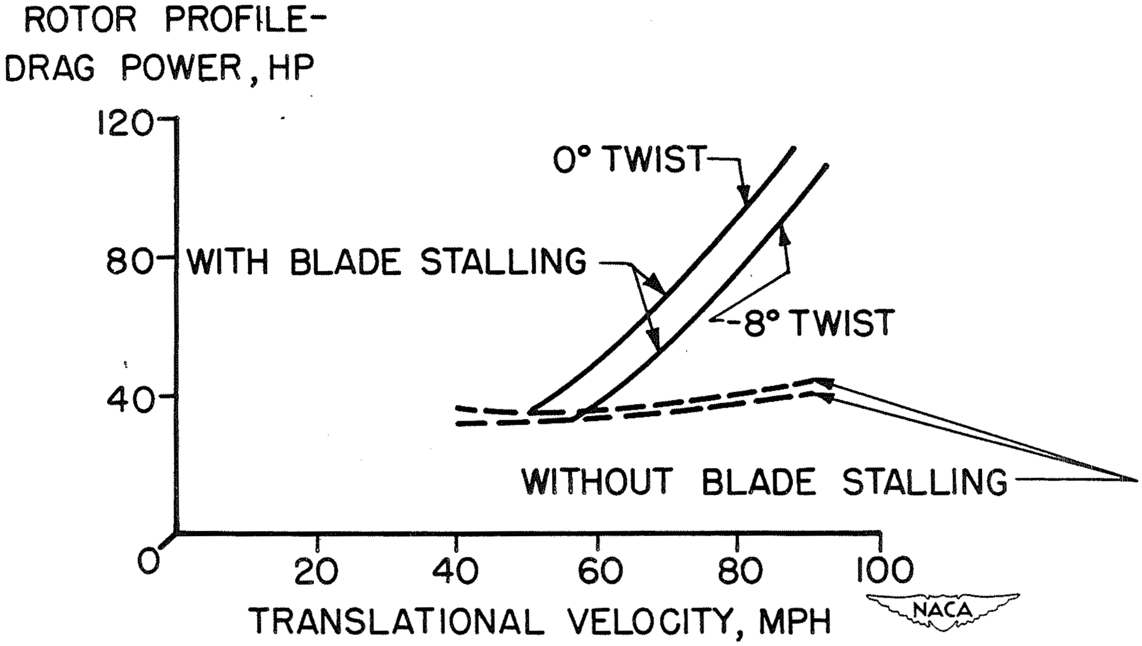

Figure 5.- Effects of rotor-blade stall and blade twist on rotor profile-drag power.

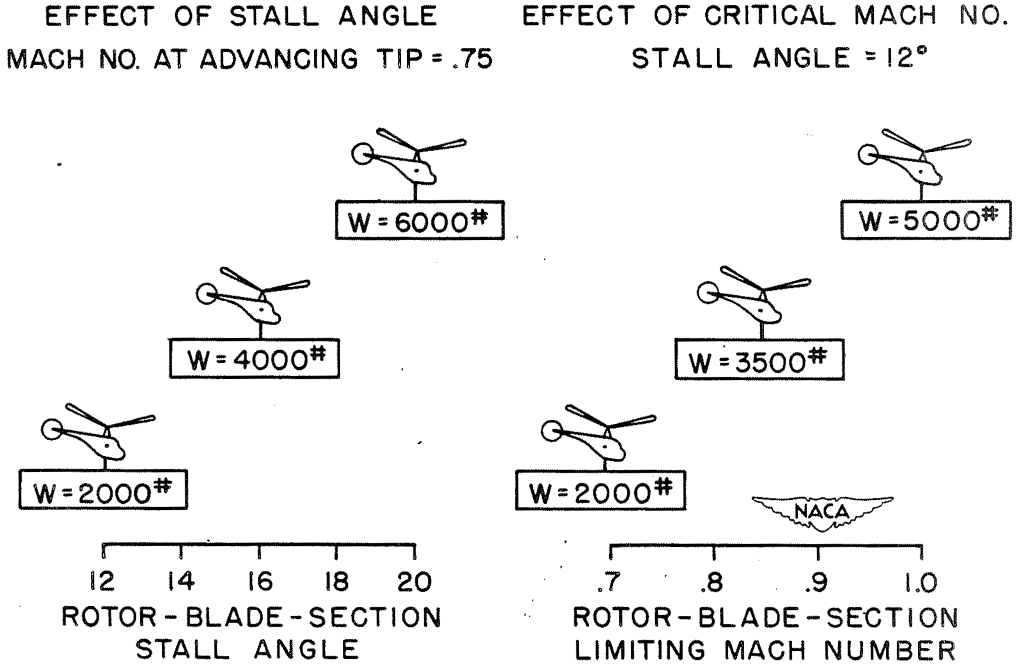

Figure 6.- Effect of rotor-blade-section stall angle and limiting Mach number on the permissible load carried by a sample helicopter.

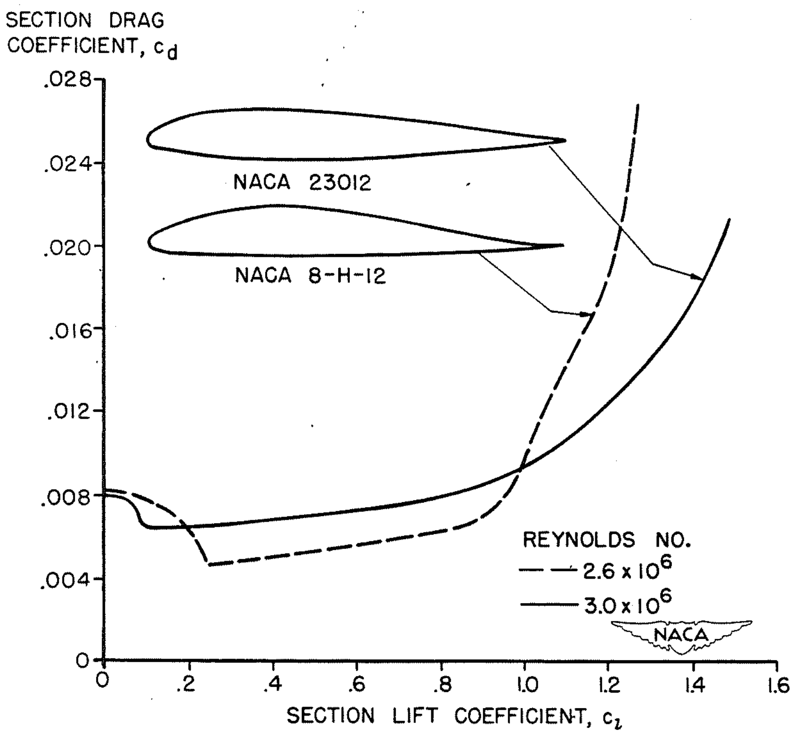

Figure 7.- Comparison of the profile-drag characteristics of the NACA 23012 and NACA 8-H-12 airfoil sections.

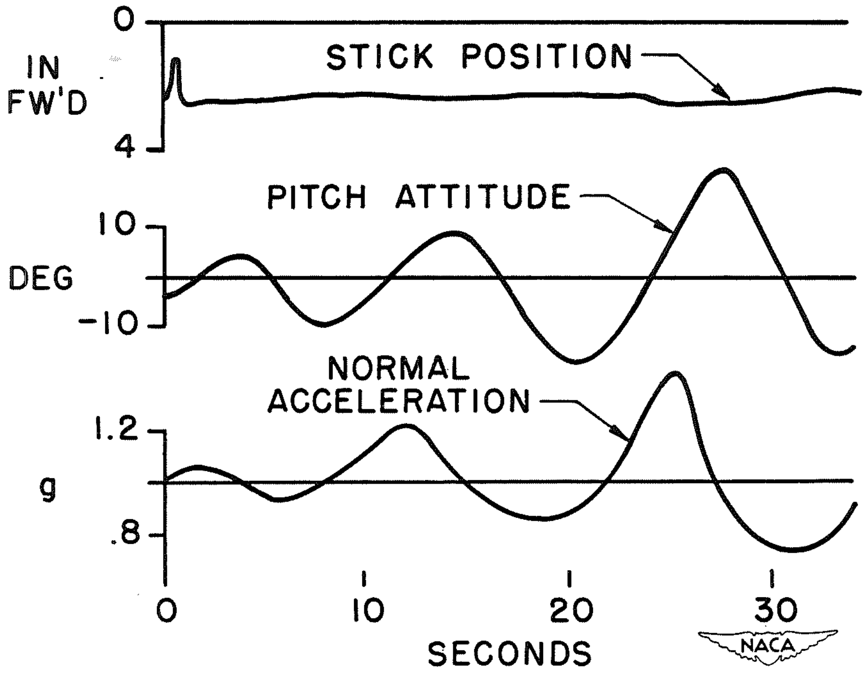

Figure 8.- Time history of a helicopter oscillation obtained in flight at 40 miles per hour.

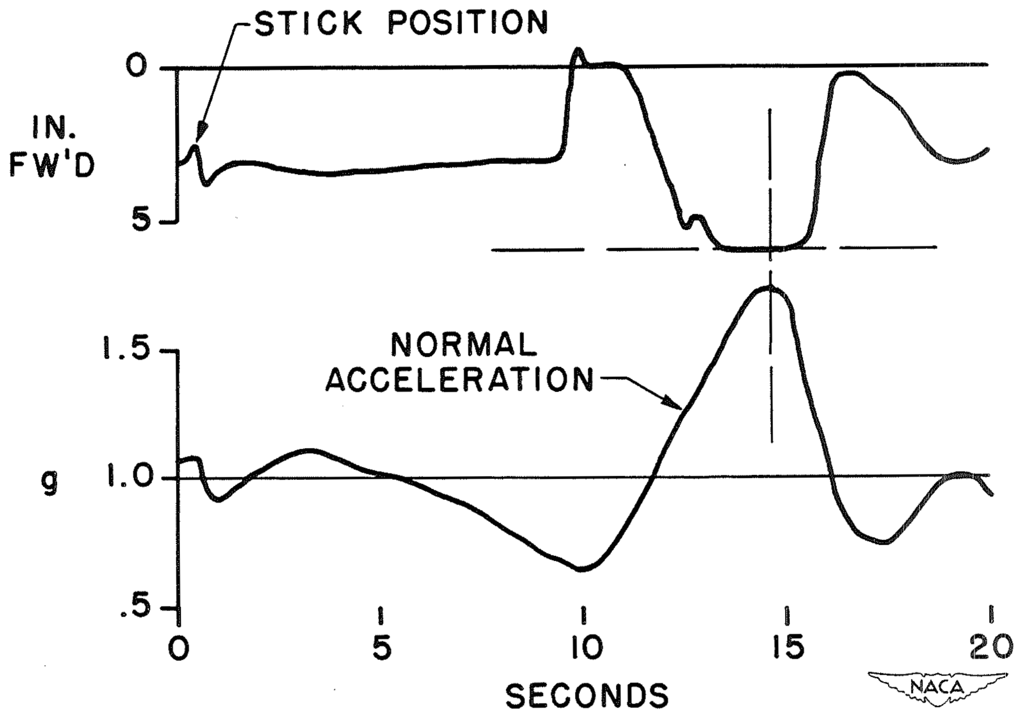

Figure 9.- Time history of the divergent motion of a helicopter obtained in flight at 65 miles per hour.